The Peculiar Type Ib Supernova SN 2005bf: Explosion of a Massive He Star With a Thin Hydrogen Envelope?

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ABSTRACT

We present $BVRI$ photometry and optical spectroscopy of SN 2005bf near light maximum. The maximum phase is broad and occurred around 2005 May 7, about forty days after the shock breakout. SN 2005bf has a peak bolometric magnitude $M_{\rm bol} = -18.0\pm0.2$: while this is not particularly bright, it occurred at an epoch significantly later than other SNe Ibc, indicating that the SN possibly ejected ~ 0.31 M$_\odot$ of ^{56}Ni, which is more than the typical amount. The spectra of SN 2005bf around maximum are very similar to those of the Type Ib SNe 1999ex and 1984L about 25-35 days after explosion, displaying prominent He I, Fe II, Ca II H & K and the near-IR triplet P Cygni lines. Except for the strongest lines, He I absorptions are blueshifted by $\lesssim 6500$ km s^{-1}, and Fe II by

$\sim 7500 - 8000$ km s^{-1}. No other SNe Ib have been reported to have their Fe II absorptions blueshifted more than their He I absorptions. Relatively weak Hα and very weak Hβ may also exist, blueshifted by $\sim 15,000$ km s^{-1}. We suggest that SN 2005bf was the explosion of a massive He star, possibly with a trace of a hydrogen envelope.

Subject headings: supernovae: general supernovae: individual (SN 2005bf) technique: photometric technique: spectroscopic line: identification

1. Introduction

The study of a subclass of hydrogen deficient supernovae, namely type Ib and type Ic events, has been one of the interesting topics in supernova (SN) research. The observational properties, progenitors, and hence the physics of explosion are the least understood for these two subclasses. The recently established connection of bright and energetic SN Ic events with Gamma-Ray Burst sources (e.g. Mazzali et al., 2003) makes their study interesting and exciting. Type Ib and Ic SNe are classified on the basis of their spectra. Both types are hydrogen deficient at maximum light, and also lack the deep Si II absorption near 6150 Å, a characteristic feature of the Ia events. At early phases Ic's do not show lines of He I, shown by the Ib's, while at later phases both types have similar spectra (Wheeler & Harkness 1990; Matheson et al., 2001; Branch et al., 2002). The Ib and Ic supernovae events are widely accepted to be core collapse supernovae (e.g. Shigeyama et al., 1990; Hachisu et al., 1991; Woosley, Langer & Weaver 1993; Nomoto et al., 1994).

Supernova SN 2005bf was discovered independently by Monrad (2005) and Moore & Li (2005) on April 5.722, 2005 (UT), at a magnitude about 18.0, in the SB(r)b galaxy MCG

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+00-27-5. The supernova was also marginally detected, at magnitude about 18.8, on a image taken on Mar. 30.31 (Moore & Li 2005). Early spectroscopic observations indicated the supernova to be of type Ic a few days before maximum light (Morell et al., 2005; Modjaz et al., 2005). SN 2005bf was reported to undergo an unusual photometric behaviour by Hamuy et al., (2005). After an initial brightening from April 7 to April 13, the supernova declined until April 21, after which it re-brightened to magnitudes brighter than the initial maximum (see light curves posted at the Carnegie Supernova Project (CSP) group website[9]). Spectra obtained during the re-brightening (Wang & Baade 2005; Modjaz, Kirshner & Chalis 2005) indicated that the spectrum had developed conspicious lines of He I similar to type Ib supernovae. Also, the SN reached a bright maximum, making it an interesting target.

In this paper we present optical spectroscopy of SN 2005bf obtained near the maximum, and optical photometry during the maximum and subsequent decline. CCD photometric and spectroscopic observations were performed with the 2-m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Hanle, India using the Himalaya Faint Object Spectrograph Camera (HFOSC).

2. The Optical and Bolometric Light Curves

Photometric observations in the Bessell $BVRI$ bands were made during May 3 − May 28. Landolt standard regions were observed on May 27 to calibrate a sequence of secondary standards in the supernova field. The magnitudes of SN 2005bf and the secondary standards in the field were obtained by point spread function photometry. The identification and magnitudes of the secondary standards in the field of SN 2005bf may be obtained from http://www.iiap.res.in/personnel/gca/sn05cal.html. The $BVRI$ light curves of SN 2005bf are shown in Figure 1. Also included in the figure with the R magnitudes are the unfiltered CCD magnitudes reported in the IAU Circulars, and the estimates made by amateurs [10]. The pre-maximum evolution of SN 2005bf was quite peculiar and different from that of other SNe Ib/c. SN 2005bf had a very slow rise to the maximum, which occurred around 2005 May 7, nearly 40 days since the shock breakout. In contrast, the type Ib SN 1999ex rose to maximum in about 18 days (Stritzinger et al., 2002). After maximum, which was broad, SN 2005bf declined with rates of 0.07 mag day^{-1}, 0.038 mag day^{-1}, 0.05 mag day^{-1} and 0.014 mag day^{-1} in B,V,R and I, respectively, which are similar to the decline rates observed in SN Ib SN 1999ex at similar epochs with respect to maximum.

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[9]http://csp1.lco.cl/∼cspuser1/images/OPTICAL_LIGHT_CURVES/SN05bf.html

[10]http://www.astrosurf.com/snweb2/2005/05bf/05bfMeas.htm

In this paper we assume the date of explosion to be 2005 March 30 (JD 2 45 3459.5), based on Moore & Li (2005) and the light curve posted by the CSP. A Galactic reddening E(B-V) = 0.045 as estimated by Schlegel, Finkbeiner & Davis (1998) in the direction of the host galaxy has been used. As the supernova occurred in one of the spiral arms of the host galaxy, reddening within the host is also expected. However, since no conspicious Na I D absorption features have been reported, we assume negligible extinction due to the host galaxy. We adopt a distance modulus of $\mu = 34.5$ for the host galaxy using $H_0 = 72$ km s^{-1} Mpc^{-1}, $\Lambda = 0.7$, $\Omega_M = 0.3$, and a redshift of $z = 0.0188$ (HyperLeda database).

The bolometric magnitudes were estimated by converting our $BVRI$ photometry, corrected for the assumed E(B-V), into absolute monochromatic fluxes adopting the magnitude-to-flux conversion factors compiled by Bessell et al., (1998). The fluxes were then integrated using a fitting spline curve. Around the light maximum, extending the spline fit only to 3600 Å give bolometric magnitudes about 0.15-0.2 mag fainter than if the fit were extended to 3000 Å, while there is no significant difference around the epochs of our last observations, indicating a significant contribution by the U flux around maximum. Hence, the bolometric magnitudes are estimated with zero-flux terminals of the spline fit chosen as 3000 Å and 2.480 μm in an effort to recover as much as possible the U and near-infrared fluxes that were missed by our photometry. Adding a conservative uncertainty, ± 0.2, to the bolometric magnitudes, we estimate the bolometric magnitude at maximum to be $M_{\rm bol} = -18.0 \pm 0.2$ on May 11 (JD 2 45 3502.1). We plot in Figure 2 the evolution of the absolute magnitude in B (M_B) for SN 2005bf since our assumed date of explosion and compare it with other SNe Ib/c, namely, SN 1999ex (Stritzinger et al., 2002), SN 1994I (Richmond et al., 1996), SN 1984L (Tsvetkov 1987; Schlegel et al., 1989) and SN 1985F (Tsvetkov 1986). The maximum bolometric magnitude (inset in Figure 2) of SN 2005bf is brighter than the average value for type Ib/c SNe, even though the time of maximum was significantly later. Furthermore, the $B - V = 0.37$ colour at maximum indicates SN 2005bf to be marginally bluer.

The rise time depends on the mass and the explosion energy (e.g. Nomoto et al., 2004). The slow rise suggests a relatively low ratio of explosion energy to ejected mass. A detailed modelling of the light curve and the spectra are beyond the scope of this work and will be reported in a later paper (Tominaga et al., 2005). However, preliminary calculations indicate a tentative value for the explosion energy of $\sim (1.0 - 1.5)10^{51}$ erg, and an ejected mass of $\sim 6 - 7 M_\odot$. The brightness of the peak and its late occurrence suggest a relatively large production of ^{56}Ni ($\sim 0.31 M_\odot$), which points to a rather massive progenitor ($\sim 25 - 30 M_\odot$) (Tominaga et al., 2005).

3. The Spectra

Spectra of SN 2005bf were obtained at a resolution of 8 Å in the wavelength range 3600–7200 Å and 5200–9200 Å on May 4.65, 6.62, 8.63 (UT) (marked by vertical lines in Fig. 1). All observations were made using a slit of 2.2 arcsec width and aligned along the parallactic angle. Spectrophotometric standards HZ 44 and BD $+33^0$ 2642 observed on 2005 May 4 were used to correct the supernova spectra for the response curves of the instrument and bring them to a flux scale. The spectra in the two different regions were combined, scaled to a weighted mean, to give the final spectrum on a relative flux scale, which were then brought to an absolute scale using the $BVRI$ magnitudes. The flux calibrated spectra, corrected for the redshift of the host galaxy are shown in Figure 3. The three spectra presented here are all near optical maximum, but are very similar to those of SN 1984L (Harkness et al., 1987; Matheson et al., 2001) about one week past maximum and SN 1999ex (Hamuy et al., 2002) 4 days past maximum. If the phase since the date of explosion is considered, then the spectra of SN 2005bf correspond to about 35-39 days after explosion, while the corresponding phase is about 20-25 days for SN 1984L and SN 1999ex.

The spectra show prominent and broad P Cygni lines of He I, Fe II, and Ca II. The He I λ5876 P Cygni feature is strong, whose identification is supported by the presence of clear He I λ6678 and λ7065, although Na I D could also contribute. He I λ7281 may also exist. However, it should be noted that this feature is affected by the telluric H_2O absorption, and our spectra are not corrected for the telluric features. The velocities corresponding to the absorption minima of the relatively weak He I λ6678, λ7065, and λ7281 (if real) have average velocities of $\lesssim$ 6500 km s^{-1}, lower than that of He I λ5876 which is $\sim$ 7300 km s^{-1}. The very strong P Cygni feature between 3700 Å and 4100 Å and the very broad one between 8000 Å and 9000 Å are obviously Ca II H&K and the near-infrared triplet, respectively, with velocities $\gtrsim$ 10000 km s^{-1}, indicating that these lines have large optical depths. Between 4000 Å and 5500 Å the spectra are dominated by Fe II multiplets, whose individual identifications are difficult due to the large intrinsic number of Fe II optical transitions and strong line-blending in the fast-moving SN atmosphere. Nevertheless, we identify Fe II multiplet 27 (λ4233), 42 (λ4924, λ5018, and λ5169), and 49 (λ5317) with velocities between $\sim$ 7500 km s^{-1} and $\sim$ 8000 km s^{-1}. The strong 4570Åfeature is a complex blend of several lines of Fe II multiplets 37 and 38, mainly $\lambda\lambda$4629, 4584, 4549, and 4520. The absorption velocity, calculated with respect to λ4520, a strong feature in both multiplets, is consistent with other Fe II lines. The identity of the P Cygni line between 6200 Å and 6500 Å is controversial. This feature, if identified as Hα, corresponds to a velocity as high as $\sim$ 15000 km s^{-1}. If, instead, identified as Si II λ6355, the measured velocity drops to $<$ 5500 km s^{-1}, which is significantly lower than all other lines. It may be noted that the uncertainty of our measurements varies from line to line and from spectrum to spectrum and can be as large as $\pm$500 km s^{-1}, a result

of the low S/N ratio, potential weak lines, and other pollution around the line absorption minima.

To further establish line identifications, we compute synthetic spectra using the fast, parameterized supernova spectrum-synthesis code, SYNOW (see Branch et al., 2002, and references therein), and show the fit to the spectrum of May 4 in Figure 4. We assume a -7 power law for the radial dependance of line optical depths. The photospheric velocity, $V_{\rm ph}$, is assumed to be traced by the absorption minima of weak lines. We first assume $V_{\rm ph} = 8000$ km s^{-1} (*lower thick solid line*), the value that matches weak Fe II lines. As expected, Fe II and Ca II lines are well reproduced, while He I λ6678 and λ7065 absorptions are a bit bluer than the observed. The observed He I λ6678, λ7065, and λ7281 (if real) are also stronger than in the model. This suggests that non-thermal excitation, which is not included in SYNOW, is important for He I. The $\sim$ 6240 Å absorption minimum is reproduced by introducing a high-velocity Hα with a lower cut-velocity of 15,000 km s^{-1} (see also Wang & Baade 2005). The narrow absorption and flat-topped emission of the synthetic Hα profile are consequences of the artifical optical-depth discontinuity of a detached line. Identification of this feature with Si II instead of Hα produces too blue an absorption minimum at 6200 Å (*dotted line*, inset in Fig. 4). An alternative identification of the feature is with Ne I λ6402 (Branch 2003). A marginally discernible dip at 4630 Å in the Fe II peak may, if real, be explained by high-velocity Hβ (marked by *arrows* in Fig. 4). Hydrogen lines have been suggested for other Ib SNe (e.g. Deng et al., 2000; Branch 2003; Wheeler et al., 1994).

We also computed a synthetic spectrum with $V_{\rm ph} = 6500$ km s^{-1} (*upper thick solid line*). This spectrum reproduces the positions of He I absorption minima, but Fe II absorptions are too red. As a possible solution, we tentatively introduce a lower cut-velocity of 8000 km s^{-1} for Fe II. One can assume Fe III dominates over Fe II below that velocity although Fe III is actually not included in our spectrum synthesis. With such a low $V_{\rm ph}$, Si II λ6355 seemingly matches the P Cygni feature between 6200 Å and 6500 Å better than the high-$V_{\rm ph}$ case. Calculations of realistic spatial structures of ionization and excitation above the photosphere are needed to correctly identify this feature and to determine the photospheric velocity, which is beyond the ability of SYNOW and the scope of this paper.

4. Conclusions

The $BVRI$ light curve and spectra of SN 2005bf around maximum are presented. The light curves indicate that the maximum occurred nearly 40 days after the date of explosion. At maximum, SN 2005bf was brighter and bluer than other SNe Ib/c. The maximum phase was broad and the decline rates slow, and may be compared with the core collapse models

of hydrogen-less cores. Preliminary calculations suggest a core mass larger than the Type Ib model suggested for SN1984L (Tominaga et al., 2005). The slow rise to the maximum and the brighter peak bolometric luminosity indicate that most of ^{56}Ni was buried in a relatively low velocity region in the very massive ejecta (Hachisu et al., 1991), although a small part of ^{56}Ni may be mixed out (Tominaga et al., 2005). The spectra of SN 2005bf around maximum are very similar to those of the Type Ib SNe 1999ex and 1984L about 25-35 days after explosion with prominent He I, Fe II, Ca II H&K and the near-IR triplet P Cygni lines present. Relatively weak Hα and very weak Hβ may also exist, blueshifted by $\sim 15,000$ km s^{-1}. We suggest that SN 2005bf was the explosion of a massive He star, possibly with a trace of hydrogen envelope.

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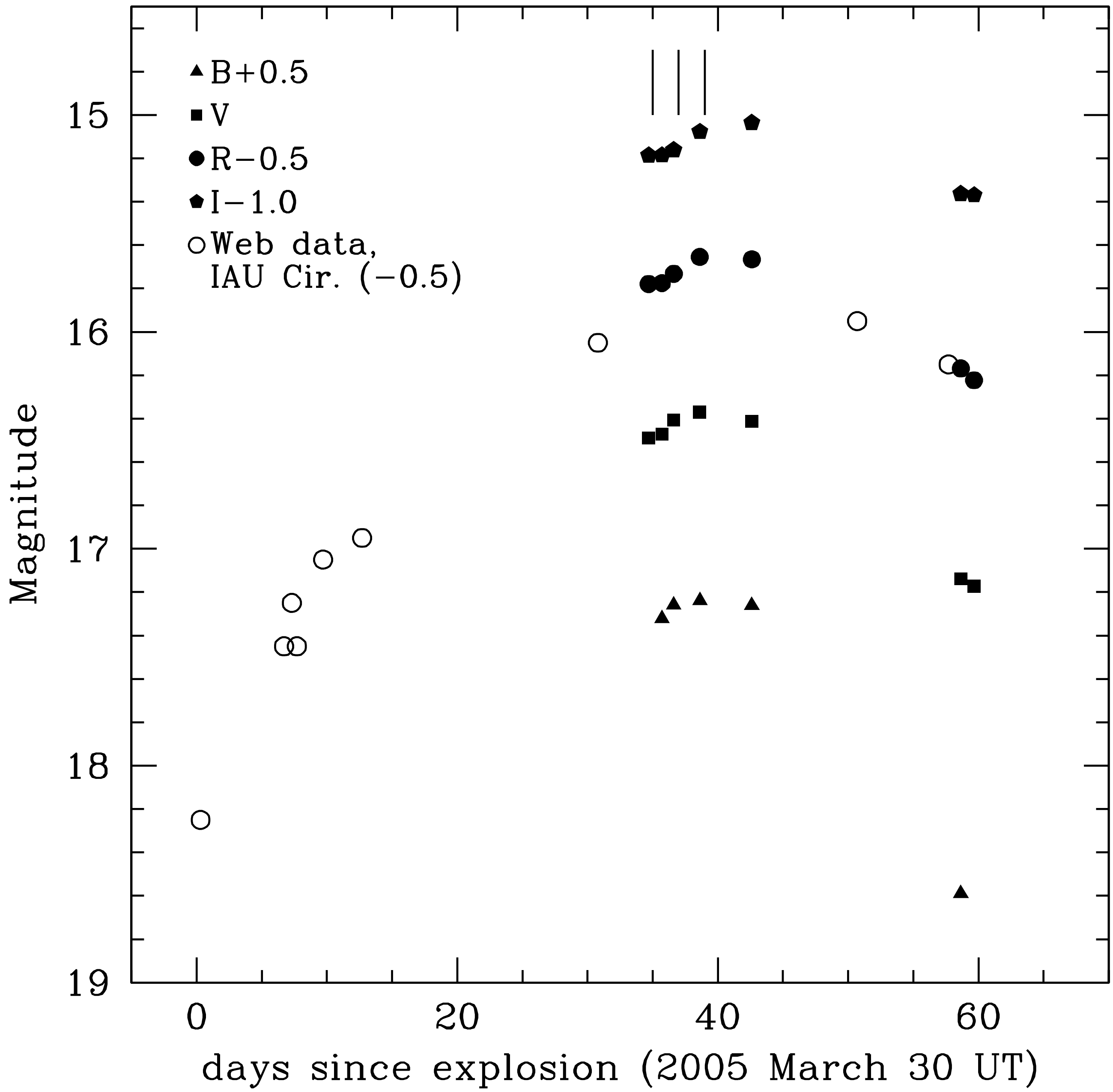

Fig. 1.— The $BVRI$ magnitudes of SN 2005bf. For clarity the BRI magnitudes are offset by $+0.5$, -0.5 and -1.0 magnitudes, respectively. Also included in the figure with the R band magnitudes are the unfiltered CCD magnitudes obtained by amateurs and those reported in the IAU circulars. Vertical lines mark the dates of spectroscopic observations.

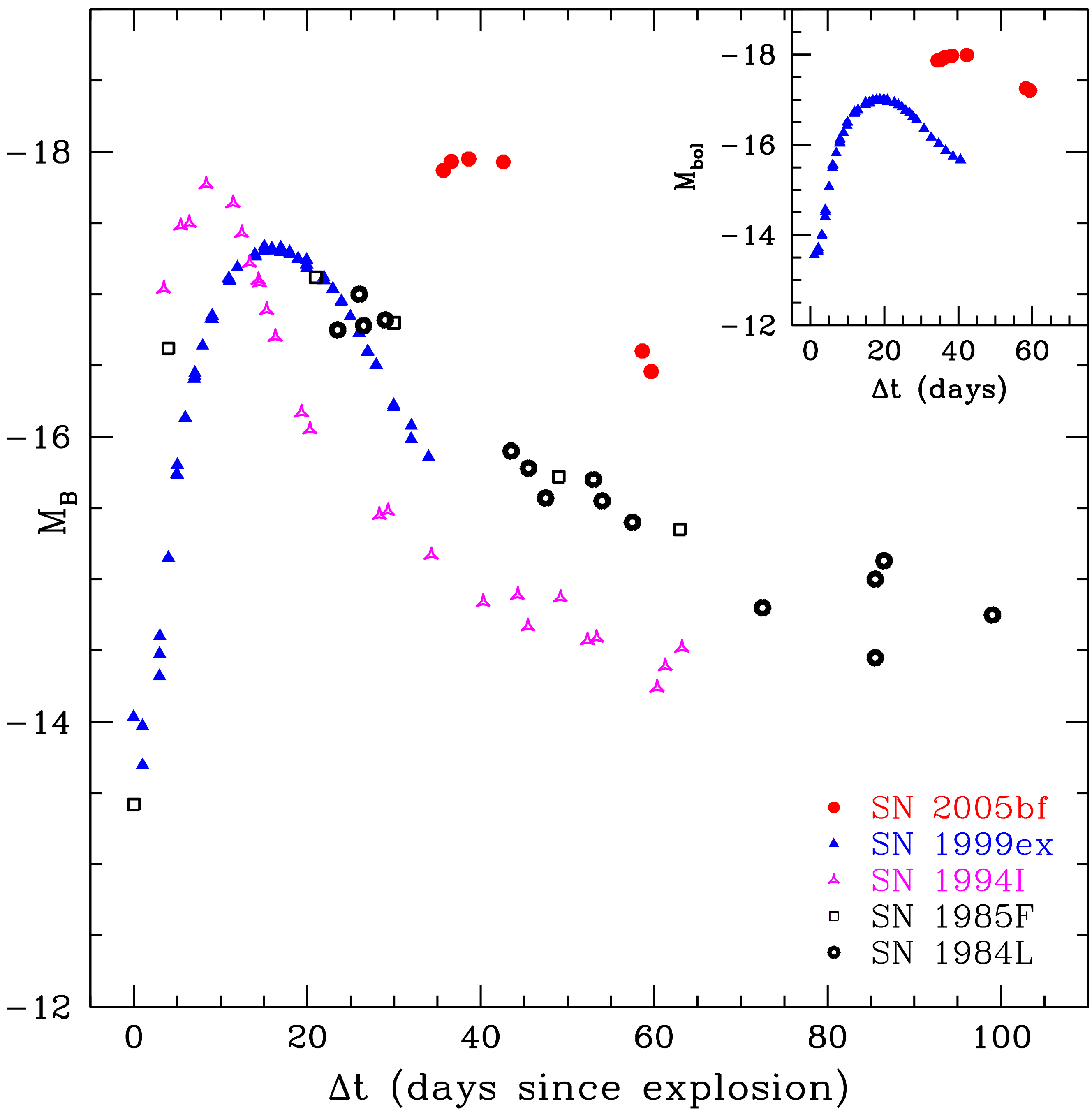

Fig. 2.— The evolution of M_B of SN 2005bf from the day of explosion compared with other type Ib/c SNe. Inset shows the bolometric light curve for SN 2005bf (filled circles) and SN 1999ex (filled triangles) for a comparison.

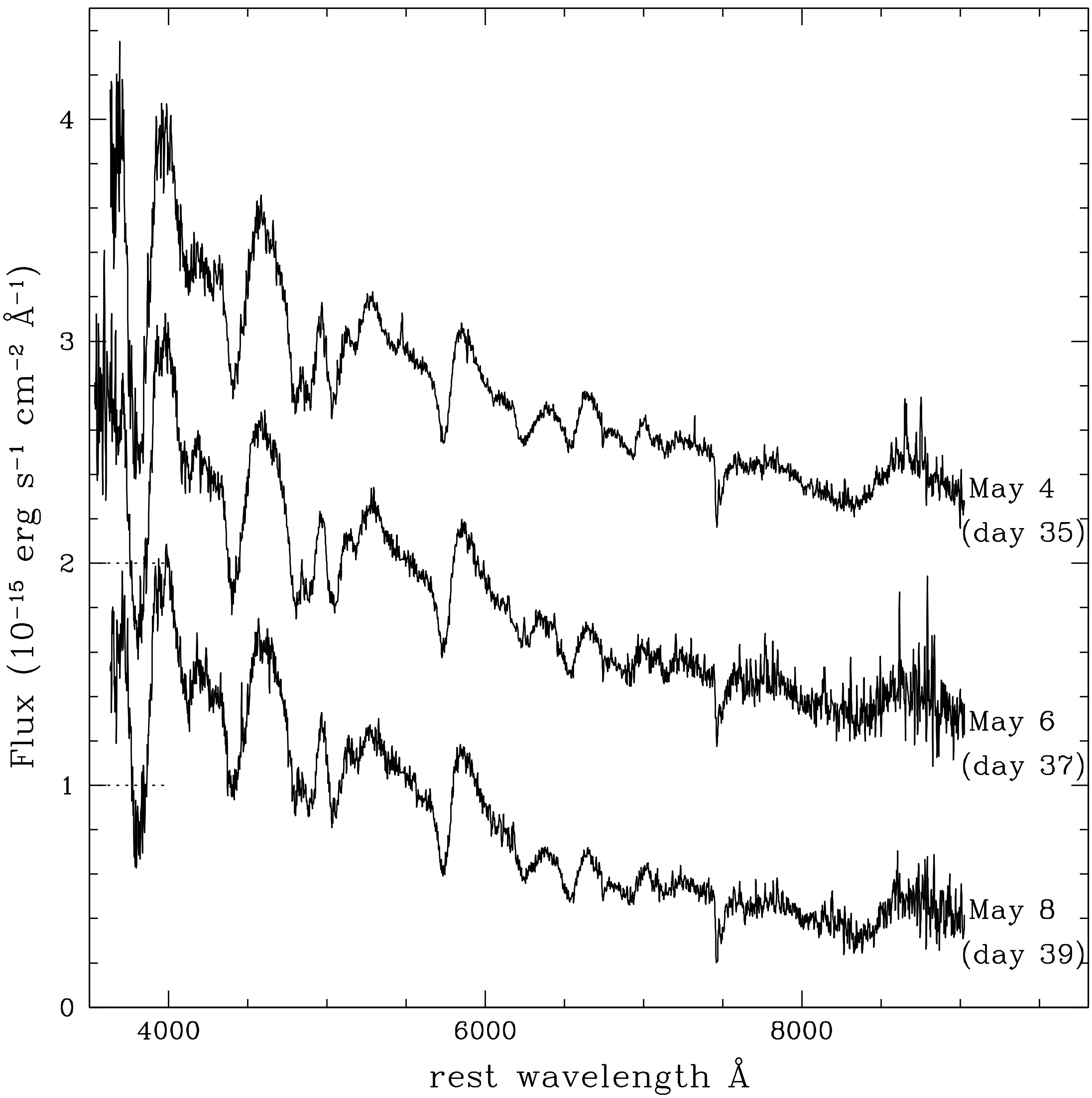

Fig. 3.— Optical spectra of SN 2005bf. The spectra are corrected for the host galaxy redshift. Time (in days) since the date of explosion is indicated for each spectrum. For clarity, the spectra have been displaced vertically. Dotted lines at the left indicate the zero flux level for each spectrum. For day 39, zero flux is the x-axis.

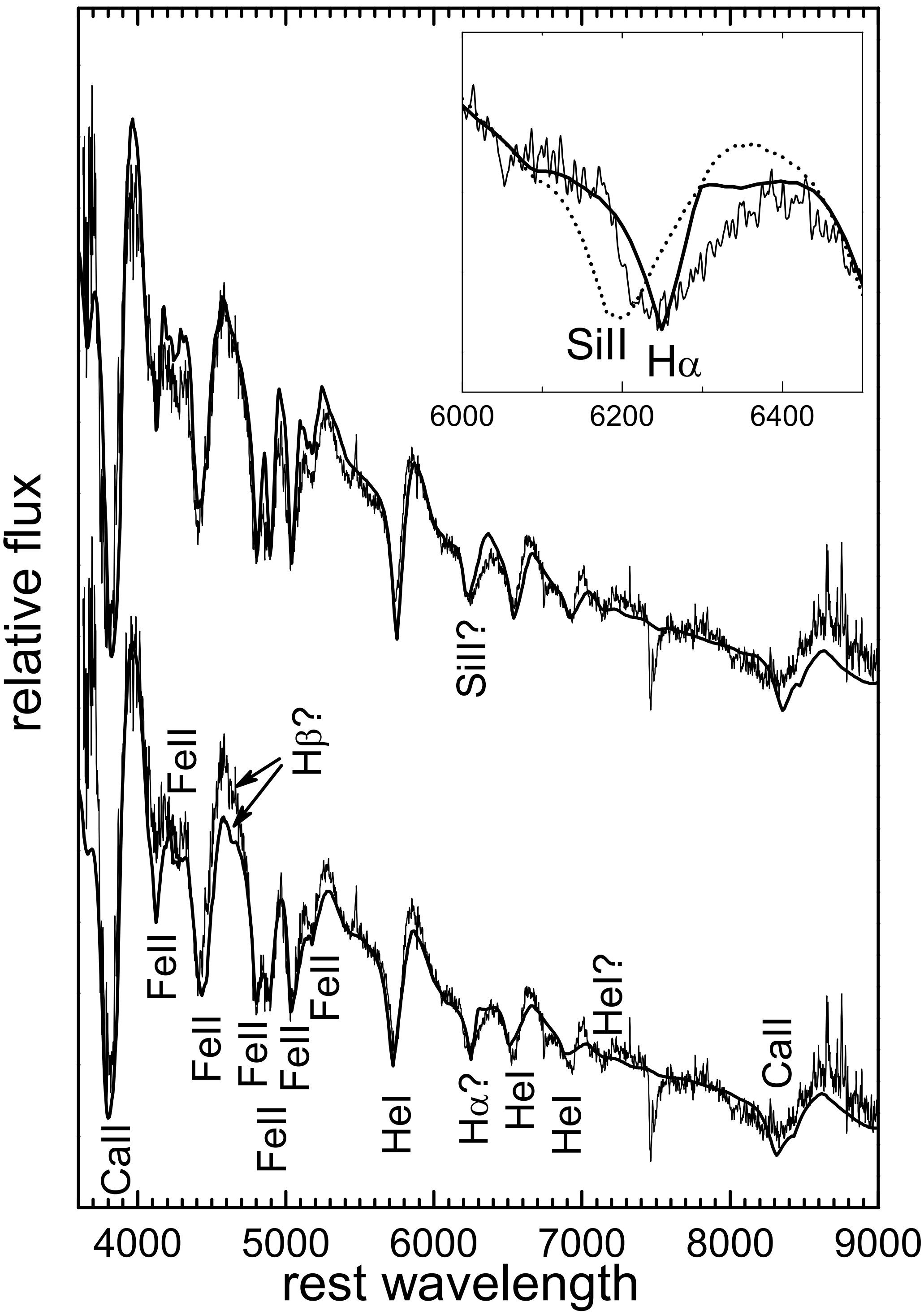

Fig. 4.— The day 35 (May 4) spectrum of SN 2005bf (thin line) compared with a synthetic spectrum (lower spectrum thick line) that has $v_{\rm phot} = 8000$ km s^{-1} and contains lines of He I, Ca II, Fe II and H. The thick line in the upper spectrum is the synthetic spectrum without lines due to H, but Si II included and $v_{\rm phot} = 6500$ km s^{-1}. Inset shows the 6245 Å absorption with fits due to Hα (thick line) and Si II (dotted line).